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Late Holocene aeolian activity in the Cimarron River valley of west–central Oklahoma

Kenneth Lepper[a,*], Gregory F. Scott[b]

[a]Department of Geosciences, North Dakota State University, 131 Stevens Hall, Fargo, ND 58105, USA
[b]USDA-NRCS, 100 USDA, Suite 208, Stillwater, OK 74074, USA

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Abstract

This investigation uses a multidisciplinary approach including geomorphic surface mapping, soil stratigraphic analysis, radiocarbon dating and optically stimulated luminescence (OSL) dating to investigate the chronology of soil formation and aeolian activation periods recorded in ridge dune deposits as well as the spatial variability of aeolian processes during active aeolian episodes. This study shows that aeolian landforms superimposed on fluvial terraces adjacent to the Cimarron River in southeastern Major County and northwestern Kingfisher County, Oklahoma are the product of distinct late Holocene climatic conditions, in which periods of dune activity are episodic and accumulation of sediments is relatively rapid. Soil-forming processes operated on the stabilized dunes during intervening periods. We also demonstrate that the synthesis of geomorphic techniques, soil stratigraphy, ^{14}C dating and OSL dating can provide complimentary and high-resolution data about aeolian activity in the Southern Plains.

Keywords: Aeolian activity; Eolian activity; Southern Plains; Cimarron River; OSL dating; Optical dating

1. Introduction

The major rivers of western and central Oklahoma are shallow sandy streams that flow generally northwest to southeast. Throughout the Quaternary, these rivers have been migrating down a shallow regional slope toward the southwest (Madole et al., 1991). In the process, the rivers have left a sequence of terraces to the northeast while reworking older terrace deposits of antecedent systems. Overprinted on this fluvial staircase is an aeolian record of dune formation and migration that reflects regional changes in sediment supply and drought. The resulting landscape is geomorphically dynamic and geochronologically complex.

The Cimarron River valley, a major feature of western and central Oklahoma, winds its way across

* Corresponding author. Tel.: +1 701 231 6746; fax: +1 701 231 7149.
E-mail addresses: ken.lepper@ndsu.edu (K. Lepper), greg.scott@ok.usda.gov (G.F. Scott).

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the Kansas–Oklahoma border in the region of the Oklahoma panhandle before it ultimately enters the body of the state from Comanche County, Kansas. It serves as the boundary between Woods County and Harper County, Oklahoma. From here, the Cimarron meanders southward and eastward to its confluence with the Arkansas River, just west of Tulsa, Oklahoma. In southeastern Major and northwestern Kingfisher counties of Oklahoma, our study area, the valley is 16–24 km wide, but with only about 75 m in elevation change from valley floor to the north divide. On the north side of the river, up to 14 fluvial terraces punctuate the valley wall from the floodplain to the divide between the Cimarron River and the Salt Fork

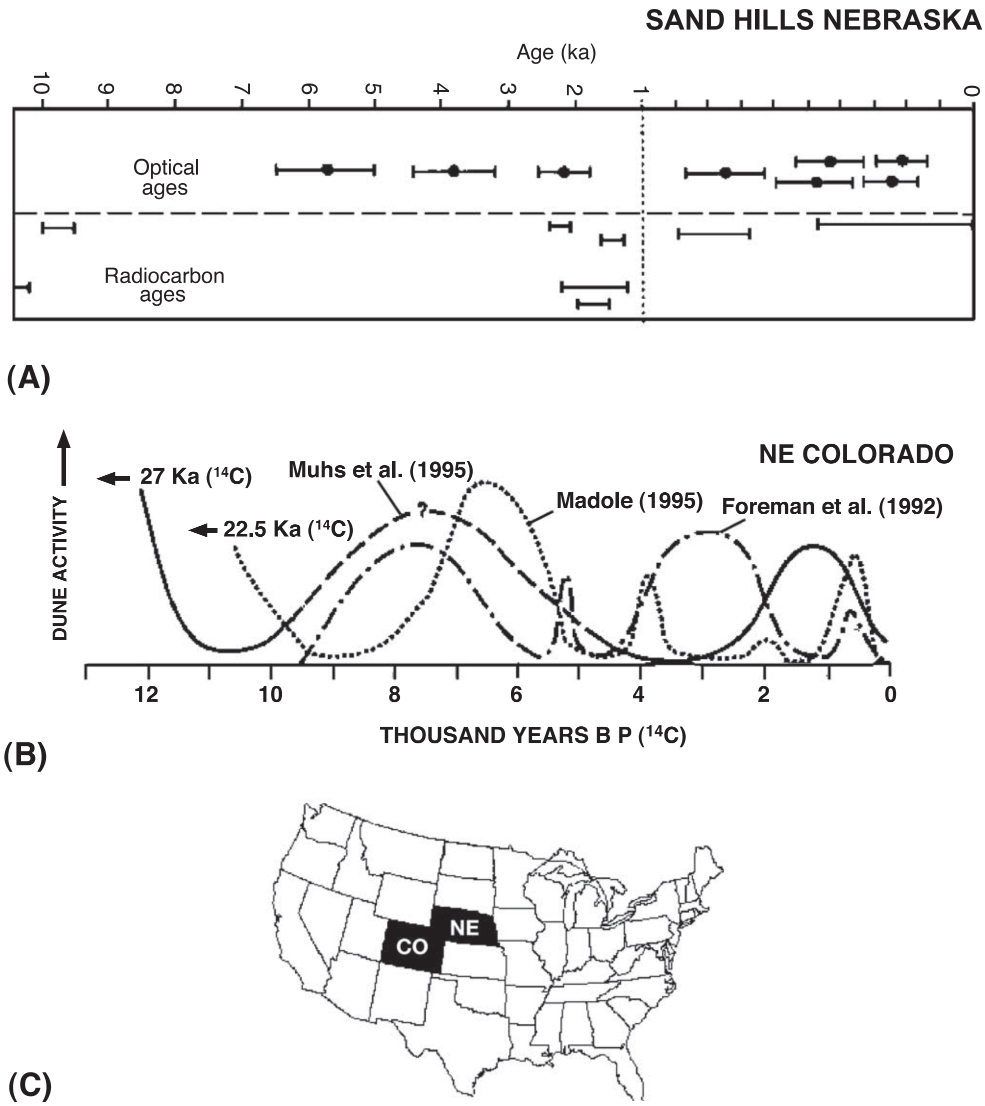

Fig. 1. Graphical results from published reports in which the timing of dune activity and dune stability seem to be at odds. (A) Coincident OSL and ^{14}C ages from one study in the Nebraska Sand Hills (modified from Stokes and Swinehart, 1997) and (B) three different studies reviewed in Dean et al. (1996) that present differing interpretations of when and how long dunes in northeast Colorado were active (original data from Forman et al., 1992; Madole, 1995; Muhs et al., 1996). Panel (C) shows the location of Nebraska (NE) and Colorado (CO) within the United States.

of the Arkansas River (Meyer, 1973; Nayyeri, 1975). This system of terraces forms a continuous ribbon on the northeast flanks of the Cimarron River extending for ~160 km from Woods County to Payne County, Oklahoma (Morton, 1980).

Aeolian activity within the valley of the Cimarron River in western Oklahoma has been an important factor in the development of the present landscape. Aeolian landforms, such as dune fields and sand sheets, are extensive on the north and east sides of the river where they mantle all or part of each of the terraces. Previous work has established a relative chronology for dunes in the area and has shown the consistency of the prevailing winds since the end of the Pleistocene (Brady, 1989). However, this study did not establish an absolute chronology of aeolian activity or study the episodic development of the aeolian landforms on the landscape.

A significant body of work exists that indicates episodic aridity and drought throughout the North American Great Plains during the Holocene (reviewed in Dean et al., 1996; Woodhouse and Overpeck, 1998). Beyond studies concerned with historical events such as "The Dust Bowl" (Muhs and Holliday, 1995; Olson and Porter, 2002), aeolian research in Oklahoma has been largely overlooked. Published reports from individual study areas with in the Great Plains often appear to be in conflict with respect to the timing of aeolian activity and soil formation [e.g., Kansas (Arbogast, 1996; Arbogast and Johnson, 1998), Nebraska (Fig. 1A; Stokes and Swinehart, 1997) and Colorado (Fig. 1B; Forman et al., 1992; Madole, 1995; Muhs and Holliday, 1995)]. Even so, regional-scale droughts and aeolian mobilization should be detectable above the background "noise" of localized occurrences.

In southeastern Major and northwestern Kingfisher counties of Oklahoma, Scott (1999) identified a sequence of eight distinct Quaternary terraces of the Cimarron River (Fig. 2). Field observations in this area have indicated that the ridge dune on the second terrace level above the floodplain of the river (Qt2) contains a record of late Holocene environmental change (Scott, 1999). The investigation reported here uses a multidisciplinary approach, including geomorphic surface mapping, soil stratigraphic analysis, radiocarbon dating and OSL dating to investigate the chronology of soil formation and aeolian activation

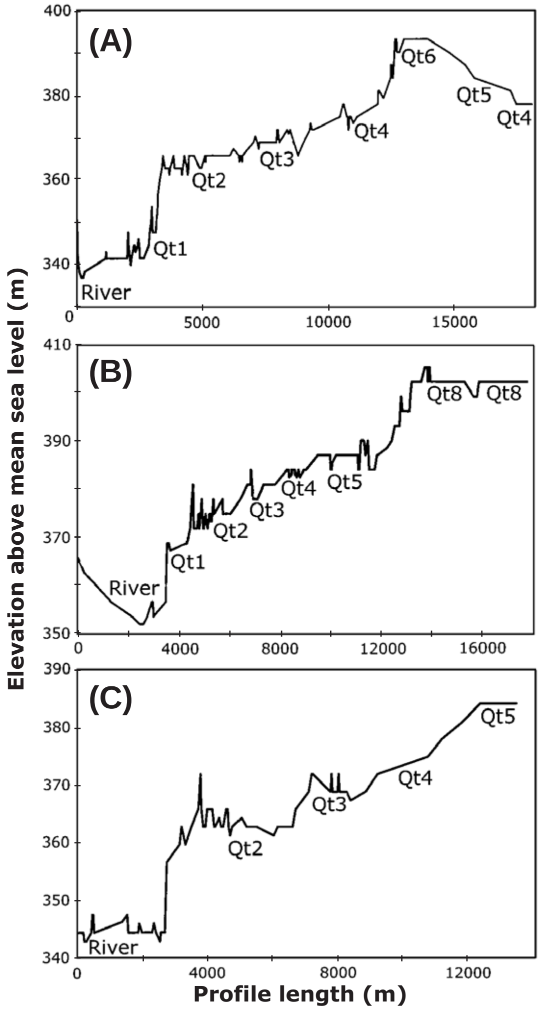

Fig. 2. Topographic profiles (modified from Scott, 1999) illustrating the river terrace levels and dune complexes identified within the study area (vertical exaggeration: ~20×). Panels correspond to Scott's (1999) cross-sections: (A) to A–A′, (B) to B–B′ and (C) to C–C′.

periods recorded in the Qt2 ridge dune deposits as well as the spatial variability of aeolian processes during active aeolian episodes.

2. Methods

2.1. Geomorphic methods

The geomorphic surfaces of 400 km^2 in eastern Major County were described and mapped in the field

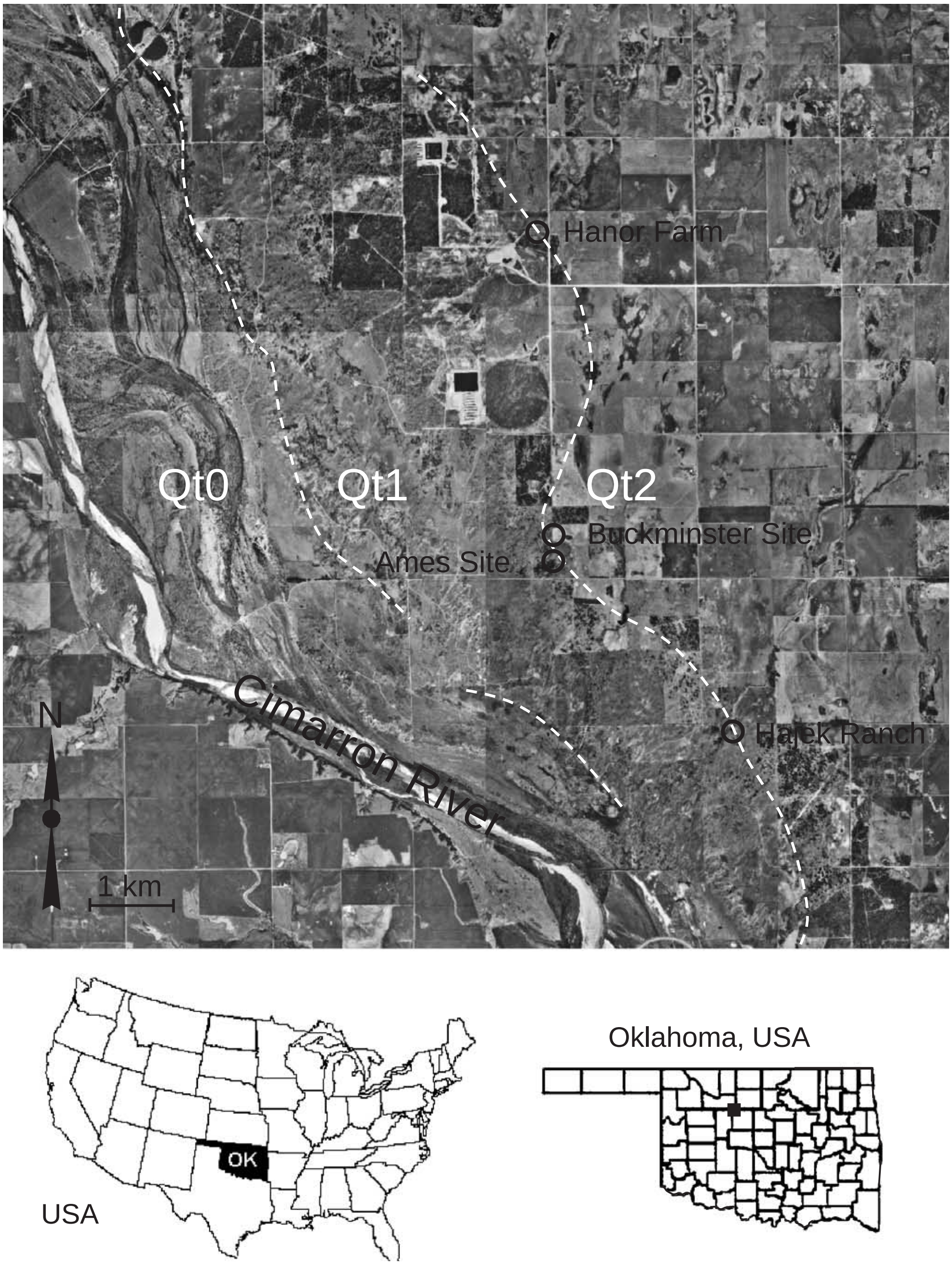

Fig. 3. Composite photograph showing the study area and sample sites adjacent to the Cimarron River in southeastern Major and northwestern Kingfisher Counties, Oklahoma. The floodplain (Qt0) and two terraces of the river are indicated (Qt1, Qt2) as well as the approximate crests of the ridge dunes on each terrace (dashed lines). The location of Oklahoma (OK) within the United States and the location of the study site (■) within Oklahoma are shown beneath the composite photograph.

at 1:24,000 scale. Field observation, aerial photography, USDA-NRCS soil survey maps and USGS topographic maps were used as resources to identify terraces, dune fields and sand sheets. The mapped area extends from the Cimarron River floodplain (T0) up to the Qt8 terrace level ~ 13 km away from the river. The Hanor Farm and Hajek Ranch sites were selected for intensive geomorphological investigation that has lead to this report. They both encompass the ridge dune complex that sits atop fluvial terrace Qt2 (Fig. 3).

2.2. Soil stratigraphy

Thirteen soil cores at Hanor Farm and eight soil cores at Hajek Ranch were taken to represent soils from all the landforms and geomorphic positions in the study area associated with the Qt2 terrace dune complex. A truck-mounted Giddings probe was used to extract the soil cores. Soils were described to the standards of Schoenberger et al. (1998) and are given in detail in Scott (1999). Buried surfaces, truncated soil sequms, indicators of age and weathering, and depositional features were of particular interest in developing the soil stratigraphy. The cores were also used to identify profiles and horizons for radiocarbon and OSL dating.

2.3. Radiocarbon dating

Three samples were selected for radiocarbon dating. At the Hanor site, a ^{14}C sample was taken from the buried soil horizon developed in fluvial deposits of the Qt2 terrace to provide a limiting age for the start of aeolian deposition on the terrace (Beta-131208). Two additional ^{14}C samples from higher stratigraphic positions within the Qt2 ridge dune complex, representing a later Holocene soil-forming period, were also collected—one at the Hanor site (Beta-131207) and one at the Hajek site (Beta-131206).

About 500 g of each sample (bulk SOM) was submitted to Beta Analytic Inc. in Miami, Florida. After pretreatment, the remaining carbon was reduced to graphite and dated by accelerator-mass-spectrometer (AMS) ^{14}C measurement. Analysis (by Beta Analytic) included calendar calibration and isotopic correction.

2.4. OSL dating

Seven samples for OSL dating were collected from backhoe pits in four dunes in the Qt2 terrace ridge dune complex: two separate dunes on the Hajek Ranch as well as sites referred to as Ames dune and Buckminster dune (Fig. 3). The pit designated "Hajek Dune 1" was excavated in exactly the same location as core 98-OK-073-3. Samples were taken from C soil horizons with intact primary sedimentary structure (low angle cross-bedding). All sample preparations were carried out under subdued lighting. Dating measurements were conducted on surface-etched quartz grains from the 125–150 μm size fraction using a Risø DA-15 automated OSL/TL reader. Green-light (526 ± 30 nm) and blue-light (475 ± 25 nm) stimulation were used. The resulting OSL signal was measured in the UV emission range (340 ± 80 nm).

Modified single aliquot regeneration (SAR) procedures (Table 1) were used to determine a set of equivalent doses (D_e) for each sample (Murray and Wintle, 2000; modified by Lepper, 2001). D_e data sets ranged in size from 23 to 103 determinations per sample. OSL ages were calculated based on the mean

Table 1
Sequence of experimental procedures used for OSL dating in this project

Sequence of procedures	Parameter definitions
Preheat	10 s at 160 °C
Measure natural signal	OSL 50 s at 125 °C
Irradiate test dose	Sample specific
Preheat	10 s at 160 °C
Measure test dose	OSL 50 s at 125 °C
4 iterations	
Irradiate regeneration[a] dose	Sample specific
Preheat	10 s at 160 °C
Measure regeneration[a] dose	OSL 50 s at 125 °C
Irradiate test dose	Sample specific
Preheat	10 s at 160 °C
Measure test dose	OSL 50 s at 125 °C
Irradiate check dose	Sample specific
Preheat	10 s at 160 °C
Measure check dose	OSL 50 s at 125 °C
Irradiate test dose	Sample specific
Preheat	10 s at 160 °C
Measure test dose	OSL 50 s at 125 °C

[a] Jargon: regeneration = calibration.

Table 2
INAA data used for dose rate calculations

Site name	Sample #	N	Conc. K (%)	Conc. Rb (ppm)	Conc. Th (ppm)	Conc. U (ppm)
Ames Dune	KL98-06	3	1.89 ± 0.10	63.32 ± 5.73	2.00 ± 0.17	0.82 ± 0.20
Hajek Dune 1	KL99-01	3	1.71 ± 0.07	59.82 ± 0.24	2.13 ± 0.40	0.62 ± 0.02
Hajek Dune 2	KL99-02C	2	1.82 ± 0.01	56.32 ± 1.42	2.28 ± 0.82	0.69 ± 0.14
	KL99-02B	2	1.78 ± 0.08	54.71 ± 4.57	2.13 ± 0.35	0.88 ± 0.07
	KL99-02A	2	1.77 ± 0.06	54.52 ± 2.12	2.10 ± 0.17	0.70 ± 0.09
Buckminster Dune	KL99-03B	2	1.91 ± 0.05	61.71 ± 0.56	1.72 ± 0.11	0.75 ± 0.16
	KL99-03A	2	1.83 ± 0.05	56.23 ± 2.75	2.72 ± 1.62	0.56 ± 0.06

D_e and standard error (S.E.) from the dose distribution of each sample (D_e data set) using the equation below

$$t_{OSL} = \frac{D_e}{D'}$$

where t_{OSL}=age (years), D_e=natural equivalent radiation dose (Gy, 1 Gy=1 J/kg) and D'=local ionizing radiation dose rate (mGy/year).

Dose rates (D') for the individual samples were calculated from the concentration of the radioisotopes of K, Rb, Th and U and their daughters in each horizon (Aitken, 1998) plus the cosmic ray dose rate at the sample depth (Prescott and Hutton, 1988). All dose rate inputs were adjusted for average water content, which was taken to be $4 \pm 1\%$ (Fisher et al., 1990). Elemental concentrations of K, Rb, Th and U were determined at The Ohio State University Research Reactor by instrumental neutron activation analysis (INAA; Table 2).

3. Results

3.1. Soil stratigraphy

All 21 cores in the study area are topped with 1 to > 6 m of well-sorted aeolian sand. The upper solums of 16 of the profiles were minimally developed, characterized by A/C, A/AC/C or A/Bw horizons (Bw—loss of primary sedimentary structure but little other pedogenesis). Six of the cores clearly exhibit characteristic low angle cross-bedding in C horizons and several cores (e.g., 98-OK-093-6 and 98-OK-073-3) show evidence of multiple soil-forming periods and soil truncations prior to or during active aeolian periods.

The surface of the buried Qt2 fluvial terrace is represented in 20 of the cores in the study area by a buried solum with a strong argillic (Bt) horizon. Soil texture, structure, worm casts and root channels all indicate a well-developed soil. The terrace surface appears to undulate and have a depression running north–south through the middle. The depression, in shape and orientation, correlates to the back-swamp position of the terrace surface. Detailed soils descriptions of all profiles can be found in Appendix B of Scott (1999).

3.2. Geomorphology/biogeomorphology

Initial emplacement and development of the ridge dune and its subsequent dune complex is thought to proceed as follows. Large areas of floodplain are dry during periods of low flow, exposing significant quantities of sand to aeolian mobilization. As the air mass encounters the terrace escarpment, the entrained material is deposited in long dunes roughly parallel to the river. This ridge dune can then be modified at later stages of the same aeolian episode or, if not stabilized by vegetation, in subsequent episodes. The dunes observed on the Qt2 terrace give evidence of the

Table 3
Radiocarbon dating results (modified from Scott, 1999)

Site name	Sample #	Depth (cm)	Measured ^{14}C age (YBP)	$^{13}C/^{12}C$ ratio	Conventional ^{14}C age (YBP)	2σ cal. age (YBP)
Hajek Ranch	Beta-131206	457–495	1110 ± 40	− 16.6‰	1250 ± 40	1275–1070
Hanor Farm	Beta-131207	307–338	1570 ± 40	− 15.6‰	1730 ± 40	1720–1540
Hanor Farm	Beta-131208	665–693	$10{,}207 \pm 40$	− 16.8‰	$10{,}410 \pm 40$	12,800–11,950

process described above: a prominent ridge dune that has been modified by northwest winter winds into large parabolic dunes, with some blowouts and longitudinal dunes. The Qt2 dune complex itself is among the narrowest of the eight terrace dune fields in the vicinity and suggests a relatively short period of aeolian activity during the formation of the Qt2 complex.

The density of surface drainage on the Qt2 terrace is minimal. Linear groupings of wetlands, occupying concave landscape positions and running parallel to each other and the river, are common

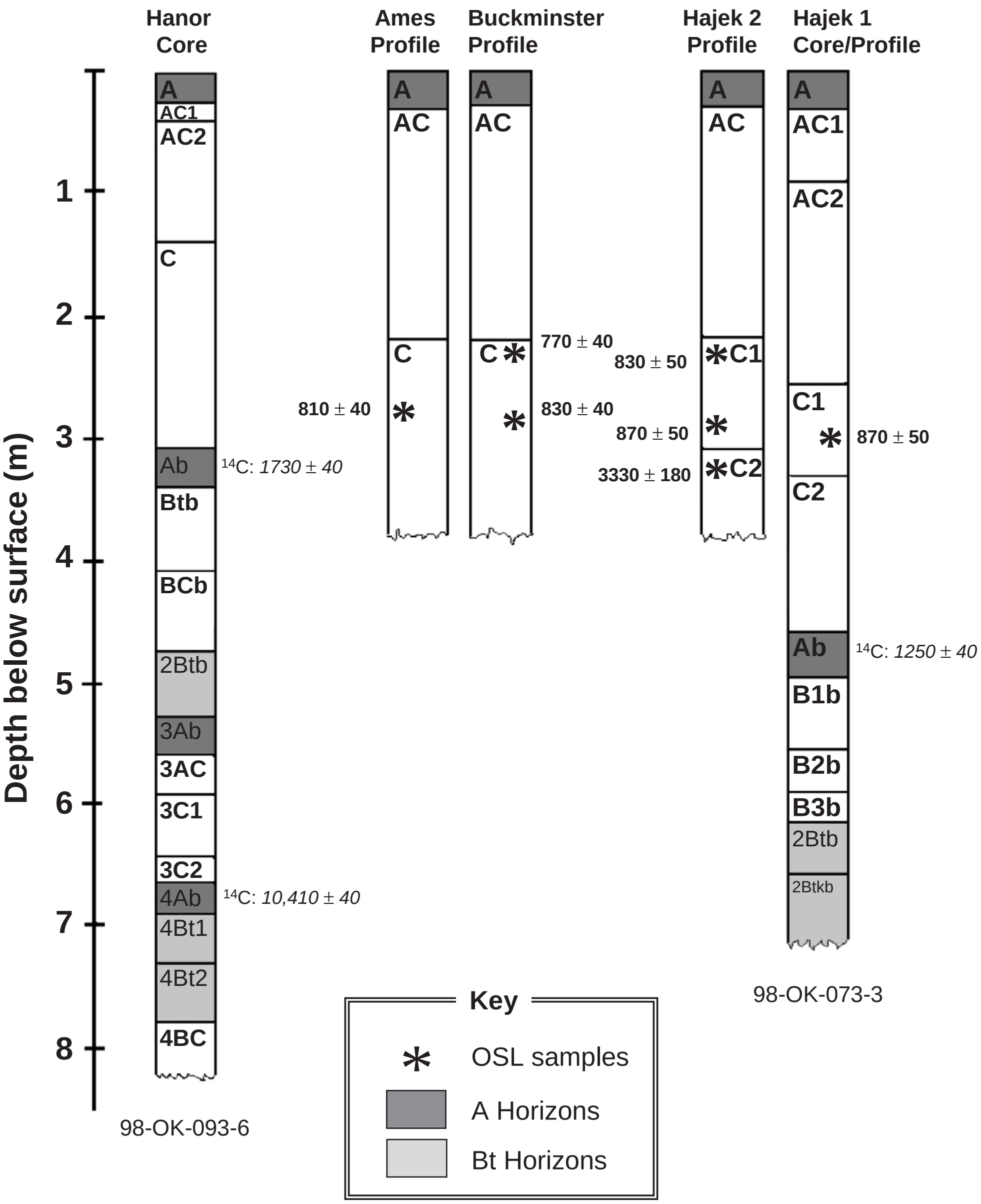

Fig. 4. Soil stratigraphic representations of the cores/profiles sampled for dating. Radiocarbon samples were taken from buried organic soil horizons (Ab); conventional ^{14}C ages are shown in italics. OSL sample locations are indicated with an asterisk (*); OSL ages are based on the mean and standard error of each sample's dose distribution.

throughout the study area. The wetlands formed because of blockage of low competence stream channels by dune emplacement. The Hanor Farm site contains one such wetland that appears to have been blocked continuously since emplacement of the Qt2 ridge dune. At the Hajek Ranch site, aerial photographs indicate that a dune dam was breached between the 1930s and 1950s.

Dunes formed on terraces closest to the river, Qt1 and Qt2, are vegetated predominantly by grasses and sagebrush. Dunes on terraces Qt2–Qt3 have a greater influence from sagebrush and oak savannah appears. Aeolian deposits on terraces Qt4–Qt7 are predominantly oak savannah with increasing degrees of cultivation (Table XI of Scott, 1999). These observations indicate that the dune complexes become progressively older–their surfaces have been stabilized longer–with increasing distance, both laterally and vertically, from the river. A geomorphic surface map of the area can be found in Scott (1999).

3.3. Dating

The results of radiocarbon dating are given in Table 3 and Fig. 4. The calibrated ^{14}C age from the lowest dated horizon at Hanor Farm (665 cm) provides a limiting age for the onset of aeolian deposition on the Qt2 fluvial terrace. This buried soil is formed in fluvial materials and represents an extended late Pleistocene/early Holocene soil-forming period that can be correlated to a regionally extensive paleosurface known as the Brady soil (Shultz and Stout, 1945). The Brady surface is overlain by aeolian deposits from, at least, one middle to late Holocene aeolian event indicated by the unconformity in the Hajek 2 profile (located by OSL analysis). ^{14}C dates from the higher stratigraphic position within the Hanor core and the Hajek 1 profile are interpreted to bracket a period of dune stability and soil formation.

OSL ages and pertinent information are presented in Table 4 and Fig. 4. All dose distributions were symmetric and Gaussian in form, which is typical of aeolian materials. Dose distributions and ages produced via green-light stimulation were entirely consistent with those obtained from blue-light stimulation—again, not unexpected for aeolian sediments. Notable, however, because either stimulation source results in the same age determination (within experimental errors) for aeolian sands. This provides some degree of confidence in correlating these types of OSL ages obtained in different studies and/or locations. The OSL ages were stratigraphically consistent with each other and with the available ^{14}C ages. Fine-scale OSL sampling in the Hajek 2 section revealed a stratigraphic unconformity between 290–325 cm that was not evident in the field (Fig. 4). The sediments below this unconformity were deposited in an aeolian activation event that occurred at 3.3 ka (OSL age KL99-02A). Because this age was obtained at only one site, the spatial extent of aeolian activity at this time could not be established.

The latest period of aeolian deposition on the Qt2 terrace complex was represented at all sites sampled for OSL dating and yielded ages of 770–880 years. The modern soils developed on these dune deposits are

Table 4
OSL dating results

Site name	Sample #	Depth (cm)	N	OSL D_e (Gy)	Dose rate (mGy/year)	OSL age (year)
Ames Dune	KL98-06	280	103[a]	1.786 ± 0.016	2.214 ± 0.079	810 ± 40
	KL98-06		23	1.778 ± 0.053		800 ± 50
Hajek Dune 1	KL99-01	300	101[a]	1.734 ± 0.016	2.005 ± 0.071	870 ± 50
	KL99-01		24	1.768 ± 0.046		880 ± 50
Hajek Dune 2	KL99-02C	230	48	1.769 ± 0.022	2.138 ± 0.076	830 ± 50
	KL99-02B	290	48	1.852 ± 0.046	2.125 ± 0.075	870 ± 50
	KL99-02A	325	48	6.881 ± 0.111	2.068 ± 0.074	3330 ± 180
Buckminster Dune	KL99-03B	225	48	1.691 ± 0.032	2.200 ± 0.079	770 ± 40
	KL99-03A	290	48	1.770 ± 0.036	2.139 ± 0.076	830 ± 50

[a] Green-stimulated OSL, all other data sets collected via blue-stimulated OSL.

consistent with formation times on the order of 500–1000 years and are in agreement with the OSL dates.

4. Discussion

The latest period of significant aeolian deposition on the Qt2 terrace complex began after 1100 AD and ended after 1250 AD (abundant OSL ages between 770 and 880 years). This event marks the onset of the most recent phase of stream blockage and wetland formation on the Qt2 terrace. Our ages for this event correlate well with paleoclimate variations in the Osage Plains reported by Hall (1988) and Woodhouse and Overpeck's (1998) "Thirteenth Century Megadrought".

OSL dates from the Hajek site indicate a truncation in the profile that was not apparent in the soil stratigraphy—highlighting a potential added benefit of OSL dating for aeolian field studies. Soil stratigraphy and OSL data confirmed that truncation of older soil profiles is widespread during active periods. This truncation would not have been discernable with radiocarbon dating because the organic soil horizon(s) had been stripped off of the 3.3 ka surface, leaving nothing to date via ^{14}C.

The color of soils developed in aeolian sands has been used in many locations in Oklahoma and Texas as an indicator of relative soil age. In this study, soil color (variation in redness) was not an effective temporal indicator. The Buckminster and Ames dune profiles were much redder than the dunes at the Hajek site, yielding Munsell hues of 2.5YR and 7.5–10YR, respectively. The soils of their upper solums are, however, identical in age. Within the study area, the bed of Cimarron River shallowly covers red sandy siltstones of Permian age. Scott has observed these rocks exposed in the riverbed during low flow periods. They occasionally serve as an iron source that can contaminate the sand blowing out of the river, thereby having a greater influence on variations in dune color than relative age.

The consistency of OSL ages demonstrates that ridge dunes adjacent to shallow sandy rivers in west–central Oklahoma can consistently record activation over reaches exceeding 5 km in length. This suggests that OSL dating may be less susceptible to local environmental and climatic "noise" than radiocarbon dating. OSL dating could be quite valuable for age correlation in large-scale projects or in integrating the results of site-scale research in the plains. Because OSL dates the actual "relocation" (transport and deposition) of sand grains, it is capable of providing a higher fidelity geochronology for aeolian activity than looking for gaps in soil formation periods via radiocarbon dating. In this regard, OSL may be critical to understanding patterns of 4D aeolian activity and the frequency of paleomegadroughts.

5. Conclusions

In this study, ^{14}C and OSL dating methods produced coherent and complimentary results with a greater stratigraphic resolution than radiocarbon dating by itself could have achieved. Combining geomorphic methods, soil/stratigraphic descriptions, radiocarbon and OSL dating methods enabled us to achieve a high-resolution picture of aeolian activity at these sites.

The chronology of events recorded in the aeolian deposit on the Qt2 terrace of the Cimarron River in west–central Oklahoma is consistent with paleoclimate records on several spatial scales (local, regional and semi-continental). The late Holocene aeolian activity period between 1100 and 1250 AD, documented here for the first time in Oklahoma, is consistent with numerous lines of evidence and indicates a significant and sustained drought throughout the Great Plains at that time.

The success of the integrated methods and multidisciplinary approach used in this investigation provides opportunities for extended study in this area. A sampling transect across progressively higher and older terrace dune complexes could help decipher migration and entrenchment rates for the Cimarron River in western Oklahoma, further elucidate the interaction between fluvial and aeolian processes in broad river valleys, as well as reveal other locally and regionally significant climatic events.

The landforms and soils of Oklahoma record a wealth of paleoenvironmental and paleoclimatic data. And yet, because of its equally rich rewards in petroleum, the Quaternary history of the state has been largely overlooked. We hope that the utility of OSL geochronology in carbon poor environments and as a long-range correlation tool will promote and enhance Quaternary research in Oklahoma.

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